

KINEMATICS OF THE SLUMGULLION LANDSLIDE FROM UAVSAR DERIVED INTERFEROGRAMS

Brent Delbridge¹, Roland Bürgmann¹, Eric Fielding², Scott Hensley²

¹University of California, Berkeley, California, USA

²Nasa Jet Propulsion Laboratory, Pasadena, California, USA

ABSTRACT

In order to measure the response of the Slumgullion landslide to hydraulic forcing, we utilize the unique capabilities of the NASA/JPL's UAVSAR airborne repeat-pass SAR interferometry system to provide surface geodetic measurements with "landslide-wide" spatial coverage. Unlike traditional space-based INSAR we are not restricted to fixed flight tracks or fixed repeat times, allowing for optimal imaging geometries and timing. We combine four look directions chosen based on the landslide geometry and invert for the full 3-D landslide-wide surface deformation. These observations complement ongoing GPS measurements and in-situ observations of pore-pressure and atmospheric parameters acquired by the U.S. Geological Survey.

1. INTRODUCTION

Resolving the kinematics of landslide deformation is necessary to evaluate the controlling mechanisms. An improved understanding of how landslides respond to environmental changes is essential to hazard mitigation and will have societal, environmental and financial impacts across the globe. Increasing global temperatures are predicted to lead to more frequent and intense precipitation and consequently an increased risk of landslide failure [1]. In this study we develop geodetic methods in order to examine how landslides respond to precipitation and snowmelt.

Historically, studies of landslide displacements have been limited to sparse point measurements acquired with labor-intensive terrestrial methods or GPS. The last two decades have seen the rise of space-based repeat-pass Interferometric Synthetic Aperture Radar (InSAR) as an increasingly important tool for the monitoring of active ground deformation, including landslide motion and hillslope creep. The measurement of the full landslide-wide surface deformation allows for the examination of how motion is accommodated between multiple kinematic domains that comprise the landslide, and overcomes the insufficient spatial coverage of traditional GPS point measurements. However, the application of InSAR as a fully operational landslide monitoring tool is challenged by geometric and temporal decorrelation, problems with unwrapping of the modulo- 2π phase measurements, and limitations posed by the measured deformation being projected into the line-of-sight (LOS).

In order to address these current limitations, we utilize the unique capabilities of the NASA/JPLs UAVSAR airborne repeat-pass SAR interferometry system to provide surface geodetic measurements with "landslide-wide" spatial coverage, optimal imaging geometries and temporal resolution of our choosing. Unlike traditional InSAR we are not restricted to fixed flight tracks

or fixed repeat times, allowing for optimal imaging geometries and timing.

In this study we validate a new imaging technique to take full advantage of the unique airborne-geodetic UAVSAR systems capabilities to invert for the full 3-D surface deformation field at the example of the Slumgullion Landslide in Colorado, USA (Figure 1). By combining the four optimally chosen look directions we are able to extract the full 3-D velocity field, with adequate redundancy in the inversion to accurately estimate errors.

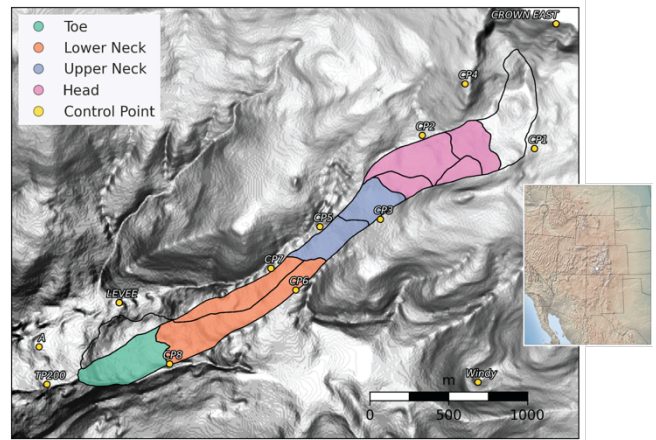


Figure 1: Shaded relief DEM of the Slumgullion Landslide and surrounding terrain. The 1/3 arcsecond DEM is from the USGS's National Elevation Dataset (NED). The black lines show the distinct geomorphic domains within the slide as identified by Schulz et al. [2]. The yellow circles represent USGS GPS control points used in this study.

2. STUDY SITE: SLUMGULLION LANDSLIDE

The Slumgullion landslide is a deep-seated landslide located in the San Juan Mountains of southwestern Colorado (Figure 1). The rapid deformation rates (2cm/day) and large spatial extent in which to examine the complex interaction of different kinematic elements make the Slumgullion Landslide an ideal target to study landslide mechanics. The currently active portion of the landslide has been deforming for the past 300 years [3] with total displacements on the order of hundreds of meters [4]. The slide sits on top of an older, inactive landslide deposit which radiocarbon dating suggests failed catastrophically approximately 700 years ago. This catastrophic failure dammed the Lake Fork of the Gunnison River forming the second largest natural lake in Colorado, Lake San Cristobal. The currently active portion of the Slumgullion landslide is measured to be ~3.9 km long and ~300 m wide.

Specifically, in this study we determine the full 3D deformation field across the entire landslide surface to explore how the landslide motion responds to the perturbation by infiltration of seasonal snowmelt (Figure 2). We also utilize all available UAVSAR data to examine how the deformation changes seasonally, and from year to year.

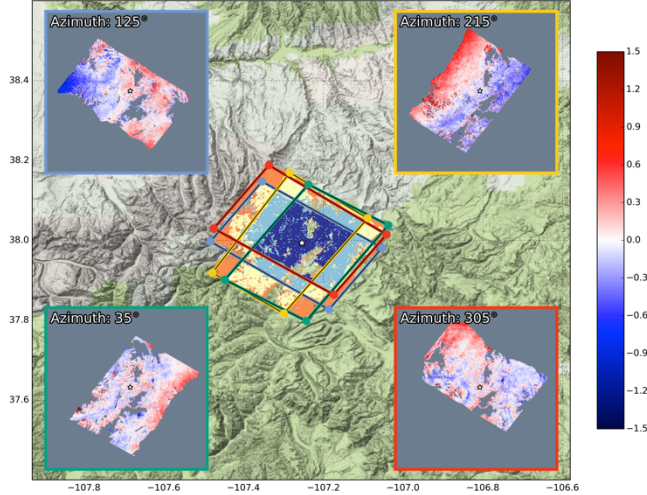


Figure 2: UAVSAR imaging geometry, and corresponding LOS Interferograms for the Slumgullion landslide. The white star shows the location of the Slumgullion landslide. The colored rectangles show the approximate non-zero footprint of each interferogram. The inset maps show the unwrapped LOS interferograms formed from UAVSAR acquisitions on April 16th and April 23rd 2012. All of the interferograms plotted show the unwrapped phase where we have converted the phase to LOS velocity to units of centimeters per day. For reference, the count of the actual number of LOS observations for each pixel provided by the four April 2012 interferograms is shown beneath the rectangles, where orange, yellow, light blue and dark blue denote 1, 2, 3 and 4 LOS observations per pixel.

3. UAVSAR INTERFEROGRAMS

The NASA/JPL UAVSAR airborne repeat-pass SAR interferometry system is flown aboard a NASA Gulfstream

III and is capable of acquiring L-Band (24 cm wavelength) SAR images with a resolution of 1.9 m in range and 0.8 m in the azimuth direction [5]. In order to provide accurate repeat-track InSAR images the NASA airplane uses a Precision Autopilot [6] with real-time differential GPS in order to repeat flight paths within a 10 m diameter tube, and typically achieves a repeat-track baseline of less than 5 m [5]. Additionally an electronically steered antenna uses real-time attitude-angle measurements in order to compensate for the changes in the aircraft yaw from flight to flight, which unmitigated by the steering would well exceed the fractional beamwidth accuracy required in the antenna look direction for repeat-track interferometry. In addition to selecting the processing parameters for motion alignment to ensure co-alignment in the along-track and cross-track directions in the generation of single look complex (SLC) images, UAVSAR SLCs require an additional empirical baseline correction to provide accurate estimates of the deformation on the scale of millimeters.

3.1. Unwrapping

The left panel of Figure 3 shows unwrapped interferograms formed from 9 pairs of acquisitions acquired on 16 flights spanning 2.6 years (953 days) from August 22, 2011 to April 14, 2014. The duration between flights is approximately one week for each pair. In all of the images the landslide deformation is clearly visible with large negative velocities (blue pixels) denoting movement away from the left-looking UAVSAR imaging system for the flight line heading of 125°. The three pairs with the largest durations (Upper Right Pane: May 9 – May 17, 2012; Center Pane: April 22 - May 03, 2013; Lower Left Pane: May 10 – May 20, 2013) fail to unwrap correctly across the center of the landslide where the deformation rates are the highest. These data were unwrapped using the traditional ICU method and are available for download from the Alaska Satellite Facility (ASF, <https://www.asf.alaska.edu>).

The series on the right of Figure 3 shows the same data unwrapped using an open-source Python phase-unwrapper implementing an algorithm based on reliability following a noncontinuous path which does not require choosing a starting point [7] (<https://pypi.python.org/pypi/unwrap>). The center panel still shows a phase ambiguity across the image, however the region of interest across the landslide no longer shows the erroneous change in sign. For the images with durations of ~ 7 days we have masked out pixels with correlation values less than 0.4, for the 3 images with durations exceeding 7 days we used a correlation cutoff of 0.55. Also note that the last image only has a duration of 3 days, and for this image no mask was used.

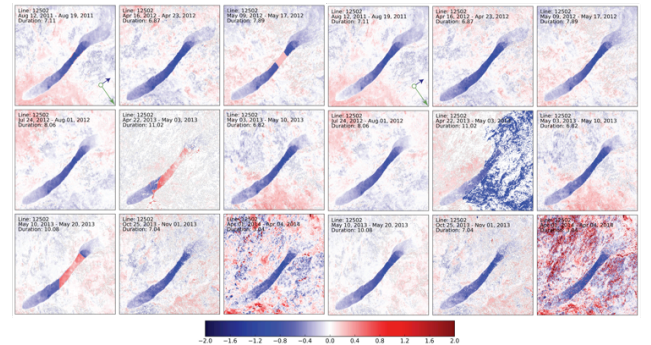


Figure 3: Unwrapped interferograms for Slumgullion flight line 12502 formed from two sets of UAVSAR image acquisitions (Dates shown in text for each pane). The series on the left shows interferograms unwrapped with the traditional ICU method, the series on the right are the same interferograms unwrapped with the reliability-based algorithm [7]. The green arrow shows the flight heading, and the blue arrow shows the radar look direction. The unwrapped phase change has been converted to velocity in units of centimeters per day.

3.2. Reference Pixels

In order to choose a proper reference pixel we utilize stable control points installed near the landslide by the U.S. Geological Survey (USGS) in 1998, which complement actively moving GPS monitoring points on the landslide.

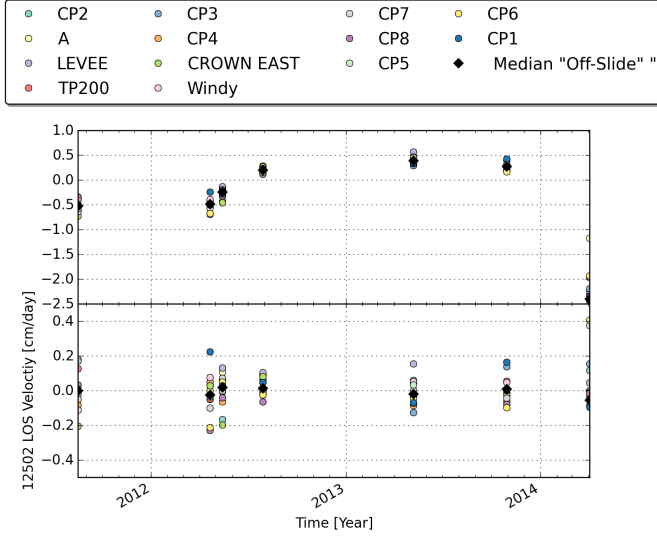


Figure 4: Estimated LOS velocity of pixels around stable control points near the Slumgullion landslide shown as measured along line 12502. The black curve denotes the median of all pixels located outside of the landslide and within the bounds of the region shown in Figure 3. The lower panel shows the same velocities with the median velocity at each given time period removed.

The location of these control points is shown in Figure 1. These points are known to be stable and not actively displacing. The top panel of Figure 4 shows a timeseries of estimated LOS velocity at each of these sites. While the variation over time is significant the variation is consistent across all control points. The lower panel shows a timeseries of the spread of each measurement about the median velocity of all the control points at the time of each measurement. To obtain the velocity of points on the landslide we subtract the median velocity of the stable control markers for each interferogram. As an estimate of the error in our data we will use the standard deviation of the velocities shown in the lower panel.

3.3. Timeseries

The velocity of the Slumgullion landslide is known to exhibit systematic seasonal variations, with the landslide accelerating in the spring following snowmelt and subsequent fluid infiltration, and decelerating in the late summer. In order to examine this seasonal variation we have acquired flights during the slow season in the late summer and fall (Oct.-Nov.), during the acceleration phase in early spring (Apr.-May) and during the deceleration phase (July-Aug.). LOS velocities for each interval spanned by the interferograms are shown in Fig. 5.

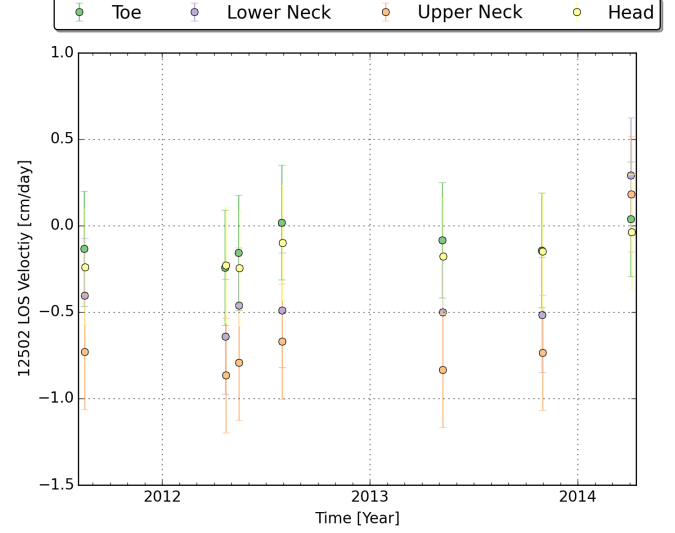


Figure 5: Timeseries of LOS velocities corresponding to line 12502. The colors denote the velocities for the geomorphic domains shown in Figure 1. The error bars are estimated from the standard deviation of the control point velocities.

4. 3D VECTOR INVERSION

To obtain the full 3D vector displacement field we combine the LOS measurements from the four flight lines shown in Figure 2. We first prepare each LOS interferogram by fitting and removing a plane to remove residuals due to baseline errors. We then normalize the phase from each interferogram to a common time interval to account for differences in the duration and acquisition times. The LOS vector is then estimated for each pixel using a DEM for the region and the acquisition flight parameters and geometry. The covariance for each pixel is estimated from the correlation matrix and we perform a least squares inversion for the displacement. The desired displacement vector is expressed in terms of the natural physical coordinates North, East, and Up.

5. CONCLUSION

We have resolved the surface kinematics of the Slumgullion Landslide by utilizing unique capabilities of the NASA/JPL's UAVSAR airborne repeat-pass SAR interferometry system. By choosing optimal imaging geometries and timings we have been able to measure the landslide-wide deformation at times crucial to understanding the landslide's response to hydraulic forcing from seasonal snowmelt in addition to mitigating geometric and temporal incoherence. We also demonstrate that unwrapping errors in these data, which could not be successfully unwrapped using traditional continuous path methods, are readily unwrapped using a reliability based noncontinuous algorithm. We have combined InSAR images from four look directions chosen based on the landslide geometry and inverted for the full 3-D landslide-wide surface deformation.

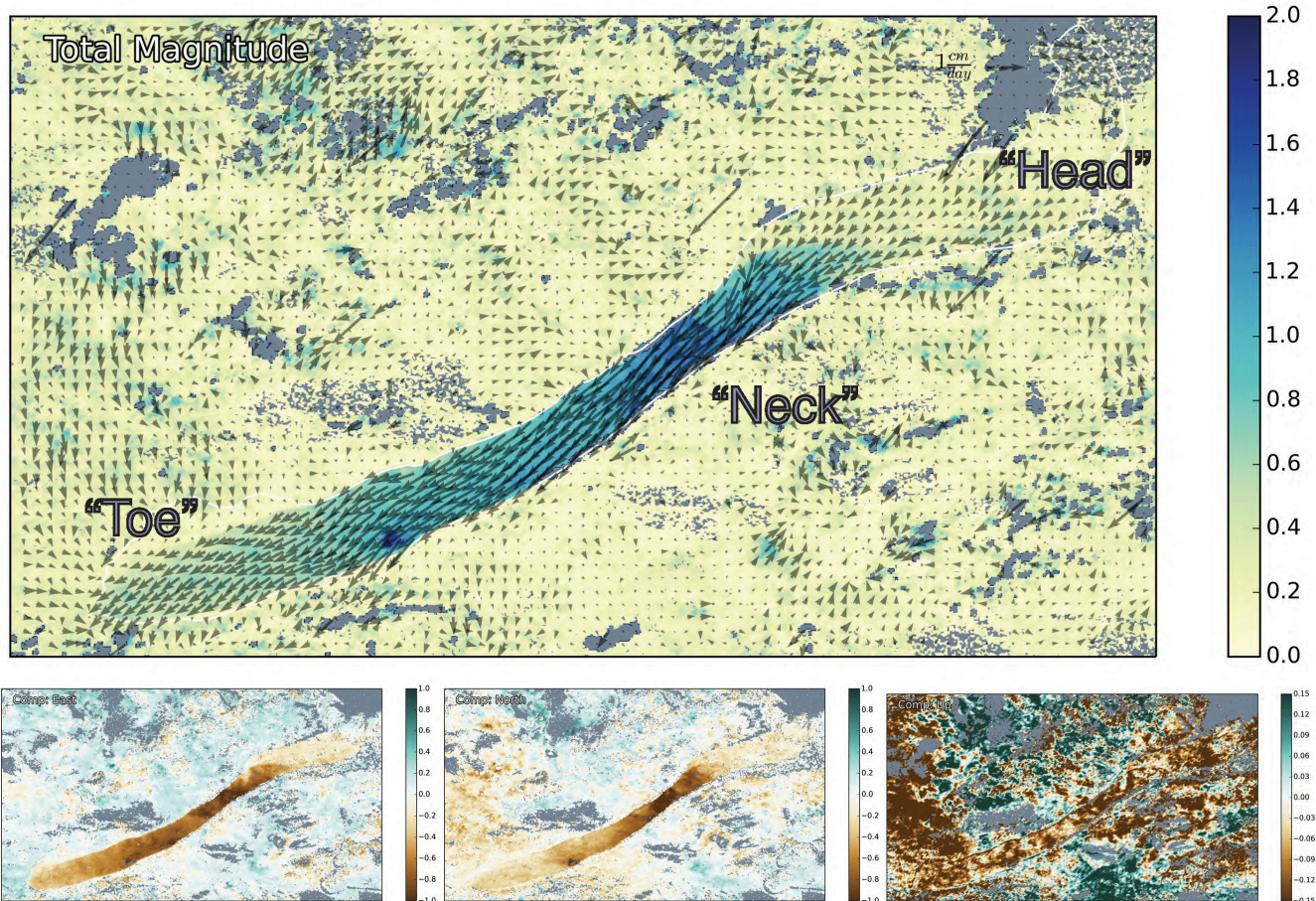


Figure 6: Results of the 3D vector inversions of the four April 2012 LOS images shown in Figure 2 in units of cm/day. The color ranges from yellow to blue corresponding to velocities ranging from 0 to 2 cm/day. The grey regions denote masked out regions of low coherence. The semi-transparent black arrows represent a downsampled representation of the same inverted horizontal velocity field. The bottom three panels show the magnitude and sign of the individual velocity components, East, North and Up respectively. The largest negative velocities are shown in brown, the largest positive velocities are shown in teal and zero velocities are shown in white. Also note that here the velocities in the East and North component range from -1 to 1 cm/day, and the vertical rates from -0.35 to 0.35 cm/day.

6. REFERENCES

- [1] J. A. Coe, "Regional moisture balance control of landslide motion: Implications for landslide forecasting in a changing climate," *Geology*, pp. 323–326, 2012.
- [2] W. Schulz, J. Coe, B. Shurtleff, J. Panosky, P. Farina, P. P. Ricci, and G. Barsacchi, "Kinematics of the Slumgullion landslide revealed by ground-based InSAR surveys", *Landslides and Engineered Slopes, Protecting Society through Improved Understanding*, Taylor & Francis Group, London, pp. 1273-1279, 2012.
- [3] R. Fleming, R. Baum, and M. Giardino, "Map and description of the active part of the Slumgullion landslide, Hinsdale County, Colorado," *open-file report*, US Department of the Interior, US Geological Survey, 1999.
- [4] J. A. Coe, W. L. Ellis, J. W. Godt, W. Z. Savage, J. E. Savage, J. Michael, J. D. Kibler, P. S. Powers, D. J. Lidke, and S. Debray, "Seasonal movement of the Slumgullion landslide determined from global positioning system surveys and field instrumentation, July 1998-March 2002," *Engineering Geology*, pp. 67-101, 2003.
- [5] S. Hensley, H. Zebker, C. Jones, T. Michel, R. Muellerschoen, and B. Chapman, "First deformation results using the nasa/jpl uavsar instrument," *Synthetic Aperture Radar, APSAR 2009. 2nd Asian-Pacific Conference*, IEEE, pp. 1051–1055, 2009.
- [6] J. Lee, B. Strovers, and V. Lin, "C-20a/giii precision autopilot development in support of NASA's UAVSAR program," *Proceeding of the NASA Science Technology Conference 2007*
- [7] M. A. Herráez, D. R. Burton, M. J. Lalor, and M. A. Gdeisat, "Fast two-dimensional phase-unwrapping algorithm based on sorting by reliability following a noncontinuous path", *Applied Optics*, pp. 7437-7444, 2002.